Multifunctional Self-Healing Structural Composites for Load Bearing Satellite Applications

A Qualitative Scoping Review

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1 Abstract

This paper presents a qualitative scoping literature review that investigates the potential of using multifunctional self-healing composites for satellite applications. As the global demand for satellites to operate in harsh space environments or extended periods of time (including thermal cycling, UV radiation, vacuum exposure and micrometeoroids impacts), improving the structural integrity and reliability of materials has become a critical engineering challenge. Carbon fibre reinforced polymers *(CFRPs) while widely used, remain susceptible to microcracking and increasing environmental degradation.

This review evaluates current self-healing mechanisms, comparing intrinsic and extrinsic systems while considering how self-healing can be integrated with other functionalities such as thermal management, electrical conductivity, structural integrity and radiation resistance. The literature indicates that using extrinsic microcapsules is the technological approach currently available due to their high healing efficiencies and passive activation. Conversely, intrinsic systems offer the potential for repeated healing cycles but remain limited by complex chemistry and challenges associated with implementation in aerospace-grade composites.

Across the literature, multifunctionality presents itself as the primary challenge rather than self-healing alone; integrating self-healing alongside structural and other performance metrics introduce significant engineering trade-offs with improvements in healing efficiency often reducing mechanical integrity, environmental durability and practical manufacturing. Furthermore, most existing research remains confined to laboratory-scale testing with limited validation under orbital conditions.

Overall, this paper concludes that multifunctional self-healing composite materials offer significant potential to extend the longevity of spacecraft operating in-orbit while enhancing their structural durability. This paper prompts and calls for future research to navigate the balance between autonomous repair and environmental and structural demands of long-term satellite missions.

2 Introduction

The number of satellites operating in Earth's orbit has rapidly increased over the past decade, with approximately over 13,000 satellites orbiting in Low Earth Orbit alone. As global reliance on satellite infrastructure continues to grow, increasing numbers of satellites are being launched while mission duration continues to extend (Gonzalo et al., 2014). To meet ever increasing demands for longer service life, satellites require materials with greater structural integrity that can withstand the prolonged exposure to the space environment. Carbon fibre reinforced polymers (CFRPs) remain among the most widely used structural materials for satellite design, due to their low-density, high-strength and stiffness properties that optimise mass reductions while maintaining high structural performance (Delkowski et al., 2023).

Despite these advantages, CFRPs still operate in one of the harshest environment conditions for engineering. During service, these polymers experience extreme environmental degradation with repeated thermal cycling, UV radiation, vacuum exposure and micrometeoroid and orbital debris (MMOD) (Di Trani et al., 2023). Collectively, these environmental stressors introduce the creation and propagation of microcracks and matrix degradation, which progressively degrade composite materials and reduce structural performance over time. As in-orbit repair remains highly limited, mitigating damage before full structural degradation has become a considerable area of research.

Self-healing composites have emerged as a promising approach in aerospace sectors – providing autonomous repair, offering the potential to repair microscopic damage without human intervention and thereby extending service life while eliminating unnecessary maintenance costs. However, autonomous self-healing alone is insufficient. Satellites need more than strength – they require thermal management, electrical conductivity, sensing and radiation resistance. Therefore, future materials must be capable of simultaneously performing several functions at once.

Although many studies investigate self-healing and multifunctionality independently, few reviews specifically evaluate self-healing as an integrated component within a multifunctional satellite composite. Furthermore, the existing field is currently confined to a laboratory-scale phase with very few progressing beyond low Technology Readiness Levels. Consequently, this paper presents a qualitative scoping literature review evaluating the current state of multifunctional self-healing composites for load-bearing satellite applications. The review compares intrinsic and extrinsic self-healing mechanisms, examines the success of integration within multifunctional composite systems, evaluates the engineering trade-offs limiting progress and identifies future research directions required to advance this field from laboratory-scale theories to aerospace-grade satellite materials.

3 Literature Review

3.1 Context

Composites are materials produced from a matrix and a reinforcement, an example being Carbon fibre reinforced polymers (CFRPs). These composites are widely used within all areas of aerospace engineering as they are lightweight, high-strength materials. However, in space, CFRPs experience environmental degradation through exposure to UV radiation, thermal cycling, and the vacuum (Di Trani et al., 2023). The matrix interface may also face flexural strength loss, microcracking, and fatigue due to radiation and debris capture (Delkowski et al., 2023). Experimental studies by Park et al. (2012) demonstrated that the strength failure results from the repeated fluctuations in temperature (between –175°C - 120°C) which generate matrix and interface microcracks. Park et al. tested approximately 2000 cycles, which was an extension from previous similar studies that tested fewer than approximately 500 cycles. Through this testing, it was found that early-stage degradation mechanisms are critical in ensuring long-term structural performance but alongside this, an understanding was reached that an improvement in one property often led to a reduction in another property. These challenges have driven interest in multifunctional composite materials that are capable of maintaining structural integrity while also responding to damage autonomously.

3.2 Intrinsic & Extrinsic Self-Healing Systems

Generally, self-healing composites can be categorised into intrinsic and extrinsic systems based on how healing is generated in the material. The extrinsic self-healing approach comes from added healing agents stored in the material. These healing agents can come in the form of microcapsules, hollow fibres, vascular networks, and more (Billiet et al., 2012). In contrast, intrinsic self-healing is generated inside the matrix by the polymer network itself through reversible covalent bonding, such as Diels–Alder reactions, or reversible non-covalent interactions, for example, hydrogen bonding or ionic bonding (Wang et al., 2023).

While extrinsic systems are limited by the finite availability of healing agents, their passive activation makes them more suitable for spacecraft applications where external intervention is not feasible. Extrinsic self-healing agents can also be added to industry-standard aerospace composites such as high-Tg matrices, whereas intrinsic systems usually require rewriting the matrix chemistry (Paolillo et al., 2021).

3.3 Mechanism of Microcapsule-Based Healing

Microcapsule-based self-healing systems operate through the release and subsequent polymerisation of a healing agent upon damage. In a study by Veeramani et al. (2023), three different dicyclopentadiene (DCPD)-urea formaldehyde (UF) based single-walled microcapsules were evaluated, comparing their impact on thermal, mechanical, electrical, and self-healing performance.

DCPD-based systems are one of the most well-researched self-healing systems due to its high healing efficiencies 90-93% in fracture toughness tests at room temperature as well as its rapid polymerisation kinetics (Vintila et al., 2020). It is often used as a benchmark for comparing alternative self-healing systems.

A polymeric shell encapsulates the microcapsule, which contains a liquid monomer acting as the self-healing agent. When a microcrack forms, under fatigue, impact, or thermal cycling, and begins to propagate through the composite, it eventually ruptures nearby microcapsules embedded in the material, releasing the healing agent. This agent then undergoes an instantaneous polymerization reaction in the presence of the surrounding catalyst. The resulting product is a polymer network that seals the microcrack and prevents further propagation and damage to the polymer structure.

This process is typically facilitated in DCPD-based systems by ring-opening metathesis polymerization (ROMP), which is initiated by a Grubbs catalyst and allows for quick crack sealing after capsule rupture.

Alternatively, an epoxy resin-imidazole reaction is another self-healing system that can be used with CFRPs. As described by Bolimowski and Boczkowska (2018), with this method a carbon-fibre reinforced epoxy composite is used as the base laminate, microcapsules containing epoxy resin are embedded in the matrix, and imidazole particles are dispersed separately as the curing catalyst. With this self-healing mechanism, as a microcrack propagates through the composite, the microcapsules are ruptured, causing the resin to flow out. The resin reacts with the surrounding polymer matrix which contains solid imidazole particles. As the resin reaches these particles, the imidazole dissolves, initiating ring-opening polymerisation of the epoxy groups, hence sealing the microcrack.

Unlike the DCPD-based systems, the epoxy-imidazole systems do not require a highly reactive catalyst such as the Grubbs catalyst, which is often prone to decomposition under certain conditions (Wilson et al., 2008). This offers its advantages where thermally demanding environments are concerned, although the reaction kinetics are generally slower.

The epoxy resin-imidazole mode of self-healing was found to be very effective for managing first-cycle damage, showing increasing healing efficiency as the weight percentage of imidazole increases. However, this healing efficiency decreased with increasing healing cycles. For example, as found by Hart et al. (2015), a 2 wt% sample of the epoxy monomer had a healing efficiency of 16%, while a 10 wt% sample had a healing efficiency of 98%. Additionally, in CFRPs with epoxy resin-imidazole capsules, the presence of these capsules detrimentally affects the baseline mechanical properties of the composite (Bolimowski and Boczkowska, 2018).

Overall, the current literature does not establish a definitive superior system for space applications, but rather highlights a trade-off between rapid, high-efficiency healing and long-term chemical stability. DCPD-based systems provide a beneficial benchmark for comparison; their high healing efficiencies and rapid crack repair make them unique and beneficial for sudden damage repair. Contrastingly, epoxy-imidazole systems provide thermal, chemical and environmental stability with the removal of the need for a reactive catalyst – despite slower reaction kinetics. However, both systems present challenges in regard to reduction in baseline mechanical properties and low reliability with healing efficiency decreasing with repeatability. As a result, it is clear that selecting a self-healing mechanism is a delicate process, dependent on the application, and the balance between structural integrity, thermal and environmental stability and healing efficiency. This highlights the need for multifunctional composites to provide greater reliability for long term missions.

3.4 Integration of Multifunctionality & Current Trends

Research into self-healing composites has expanded significantly as fibre-reinforced polymer composites continue to be widely used in aerospace, automotive and energy structures. Although these materials provide high specific strength and stiffness, they remain susceptible to microcracking, delamination, and fatigue damage that can accumulate during service. As a result, many recent studies focus on integrating self-healing capabilities into composite materials in order to improve durability and extend structural lifespan (Ahmed et al., 2025).

3.4.1 Evolution of Healing Mechanisms

Microcapsule-based systems remain one of the most widely investigated approaches in the literature. In these systems, capsules containing a healing agent are embedded within the polymer matrix of the composite. When cracks propagate through the material, the capsules rupture and release the healing agent into the damaged region where it polymerises and bonds the crack surfaces (White et al., 2001). Numerous experimental studies have shown that these systems can recover a significant portion of mechanical strength after damage. Current research has focused on improving capsule design, healing efficiency and compatibility with composite manufacturing processes while reducing any negative impact on mechanical performance.

Alongside capsule-based systems, researchers have also investigated alternative healing mechanisms that enable repeated repair cycles. Vascular self-healing systems incorporate internal channels or hollow fibres that transport healing agents to damaged regions, allowing the material to heal multiple times (Toohey et al., 2007). Intrinsic self-healing polymers represent another approach, relying on reversible chemical bonding within the polymer matrix to reform damaged molecular structures when exposed to external stimuli such as heat or pressure (Hager et al., 2010). While these approaches offer the potential for repeated healing, the literature highlights ongoing challenges related to structural performance, activation requirements, and processing complexity.

3.4.2 Multifunctional & Smart Composites

At the same time, research in composite materials increasingly focuses on multifunctional or smart composite systems, where structural materials are designed to perform additional roles beyond load-bearing (Khan et al., 2026). One of the most developed areas within this field is self-sensing composites, in which conductive nanomaterials such as carbon nanotubes, graphene, or carbon black are incorporated into the polymer matrix. These materials form conductive networks that respond to damage through measurable changes in electrical resistance or impedance, enabling real-time structural health monitoring and early detection of defects such as cracking or delamination.

In addition to self-sensing, significant research has been directed toward multifunctional composites with thermal management capabilities. The incorporation of thermally conductive fillers, including graphene and boron nitride, allows composites to dissipate heat more effectively. This is particularly important in aerospace and space applications, where thermal cycling and heat accumulation can accelerate material degradation (Tserpes and Sioutis, 2025). Improving thermal conductivity while maintaining mechanical integrity remains an active area of investigation.

3.4.3 Advanced Protection & Energy Storage

Another key area of development is electromagnetic interference (EMI) shielding and radiation protection. Conductive fillers and layered composite architectures are being explored to protect sensitive electronic systems from electromagnetic interference and radiation exposure. These functions are especially relevant in satellite structures, where shielding is required but must be achieved without significantly increasing mass. Integrating shielding capabilities directly into structural composites offers a potential route to more efficient system design.

More advanced multifunctional concepts include structural energy storage composites, where composite materials are designed to act as both load-bearing structures and energy storage devices, such as structural batteries or supercapacitors (Asp et al., 2019). These systems aim to reduce overall system weight by combining mechanical and electrical functions within a single material. Although this area shows strong potential, it remains at an early stage of development due to challenges related to safety, material interfaces, and long-term performance.

3.5 Limitations & Gaps

Across the literature, a clear consensus emerges that while multifunctional self-healing composites show significant promise, their application in load-bearing aerospace structures remains constrained by a combination of technological, economic, and practical limitations. Enhancing one property often comes at the expense of another; for example, the implementation of extrinsic microcapsule networks results in reduction in stiffness and strength that influence their suitability for load bearing applications (Kontiza and Kartsonakis, 2024). Several authors emphasise that existing approaches fail to meet the extreme environmental demands of space, particularly in terms of thermal stability and rapid healing under vacuum conditions. Multiple studies converge on the issue of low Technology Readiness Levels (TRL), with research largely confined to laboratory-scale demonstrations rather than real-world deployment. This limitation is further compounded by challenges in scalability and manufacturing integration, as highlighted by Ullah Khan and Jamshed (2025), suggesting that current systems are not yet compatible with the complexity of aerospace production environments. Although emerging concepts seek to integrate autonomous repair with thermal management, EMI and sensing, they remain largely theoretical and unvalidated in operational contexts.

The existing literature therefore demonstrates substantial progress in the development of self-healing materials, particularly within polymer-based systems, yet highlights critical gaps that limit their application in load-bearing satellite structures. Key challenges include the lack of space-qualified materials, insufficient understanding of healing mechanisms, and unresolved trade-offs with healing capability, structural performance and the integration of additional functionalities. Additionally, issues related to cost, scalability, and performance under extreme environmental conditions further restrict widespread adoption. Therefore, there is a clear need for future research to focus on the development of integrated, high-performance self-healing composites that can meet both structural and environmental demands, bridging the gap between laboratory innovation and real-world aerospace applications.

4 Methodology

4.1 Research Approach

The area of self-healing composites in space presents a unique challenge in study as there is no standardised experimental methodology or universally agreed performance benchmark against which new data is meaningfully measured (Paolillo et al., 2021). The field of self-healing composites in space applications is still in its preliminary stage, with a body of knowledge dispersed across polymer chemistry, materials engineering, and aerospace science. Hence, this study has adopted a qualitative research methodology to interpret, synthesise, and critically evaluate existing knowledge rather than numerical data.

The specific methodological approach employed is a systematic literature review, a form of secondary research involving the structured identification, selection, evaluation, and synthesis of existing peer-reviewed work on a defined topic (Tranfield et al., 2003). Rather than generating experimental data, this paper explores published academic literature as the primary source of evidence to explore the inherent and functional capabilities of self-healing composites. Most importantly, this paper aims to explore the integration of self-healing mechanisms within multifunctional composite for long-term space exploration. The qualitative lens allows for a deeper understanding of space-composites and the conceptual gaps that limit the implementation of these materials in real-world applications.

The reasons this methodology was selected as the most appropriate approach for this study:

4.1.1 Absence of a Mature Experimental Evidence Base

As aforementioned, the study of self-healing composites is still preliminary in which the vast majority of research remains at the laboratory scale (Ullah et al., 2016; Paolillo et al., 2021). Many healing chemistries such as extrinsic microcapsule-based healing systems using DCDP/Grubbs' catalyst, and intrinsic reversible bond systems such as Diels-Alder reactions have been demonstrated in the controlled environment of laboratories but are yet to be validated under true environmental stressors of space like extreme thermal cycling, vacuum, hypervelocity debris, and ionising radiation (Kanu et al., 2019; Zamal et al., 2020). Considering the scope of this study, conducting original experimental work in this context would neither be feasible nor particularly meaningful without situating it within what is already understood. The literature review approach allows existing experimental findings to be gathered, compared and synthesised to establish a credible knowledge base from which future empirical work can draw from. This methodology facilitates the identification of trends, and areas of uncertainty that are later explored and interpreted throughout the discussion of this review.

4.1.2 Breadth of the Field Demands Synthesis

The study of self-healing composites spans multiple disciplines, each of which has contributed unique perspectives to a growing body of research. A literature review uniquely allows for the integration of findings across these disciplines, revealing patterns, contradictions, and gaps that would remain invisible if the study were confined to a single experimental domain. Additionally, the breadth of study demands specialist manufacturing facilities including vacuum chambers, hypervelocity impact facilities, and access to radiation testing environments which are beyond the scope of this research. Therefore, the literature review methodology provides an appropriate means of addressing the research goals.

4.2 Selection Criteria

The selection of literature for this review was guided by the PRISMA method (University of Leicester, 2023), adapted to suit the scope of a scoping literature review. The first factor to address was how relevant sources were identified. This was done through searches of academic databases such as Scopus, Google Scholar and publisher platforms (e.g. Elsevier, MDPI, Springer). Search terms included combinations and variations of keywords such as 'self-healing composites', 'intrinsic healing', 'extrinsic healing', 'CFRPs' and 'aerospace applications'. This produced an initial collection of sources concentrating on self-healing mechanisms in fibre-reinforced polymer systems.

Once the sources were identified, they had to be screened based on their relevance to the research focus. At this stage, papers that did not directly discuss self-healing behaviour in composite materials or that did not address aerospace applications were excluded. For instance, papers that studied similar fields, such as non-self-healing composite design or artificial intelligence, were not considered further. Additionally, to preserve focus on load-bearing aerospace systems, any studies focused on non-structural or non-composite applications were also excluded.

Following screening, the remaining studies were evaluated according to the technical contribution. Studies that experimentally validated self-healing behaviour were given priority, especially those that looked at intrinsic and extrinsic mechanisms in carbon fibre reinforced polymer matrices. In contrast, studies that either did not assess multifunctional testing including structural or mechanical performance or did not provide enough information on healing mechanisms were disregarded. Further, where more focused experimental research papers were available, general review papers were used sparingly only to supplement background knowledge.

In summary, using a PRISMA-informed approach made sure that the final studies selected aligned with the aims of the review. The chosen studies supported a focused, unbiased comparison and collation of intrinsic and extrinsic self-healing systems and their relevance to aerospace composite applications.

4.3 Limitations

Several limitations should be considered. Due to the rapid evolution of the self-healing field, there are many newly emerging studies that may not be captured within the scope of this review. In addition, this review relies on already published literature and may be subject to unconscious or conscious bias, where studies that presented positive results may have been overly embellished. Finally, direct comparison remains limited due to differing methodologies and measuring metrics between the different experiments, testing and healing systems. This is due to the absence of standardised testing and measurement protocols on the account of the preliminary stage the field remains in.

5 Discussion

5.1 Environmental Constraints

The environment that satellites operate in requires a transition from laboratory scale mechanical recovery to operationally viable reliability over time. The static testing of polymers has demonstrated very high 'healing efficiencies' greater than 100%. However, this type of testing does not take into consideration all the synergistically occurring environmental factors associated with Low Earth Orbit conditions such as radiation induced embrittlement, extreme temperature fluctuations (–175°C to 120°C), and ultra-high vacuum conditions. These conditions can result in mass loss due to out-gassing from the polymer matrix and potentially deactivate healing agents. Additionally, the radiation induced embrittlement can occur faster than the repair process (Suliga et al., 2026; Pernigoni et al., 2023).

Further complicating matters, impacts of micrometeoroids and orbital debris (MMOD) cause the largest issues regarding the integrity of space satellites where the damage is not repairable. These impacts cause a loss of functionality and can end a mission. Once an aerospace component is placed in space, it cannot be repaired manually by astronauts; therefore, a mechanism must provide protection against both hypervelocity MMOD impacts and ensure structural integrity during long-duration missions where the stressors are present continuously (Turicek et al., 2026). Vacuums in space causes material outgassing where gases are released and can condense onto electronics within the spacecraft rendering them nonfunctional. Self-healing materials based on siloxanes and vitrimers which have good thermal properties provide good vacuum stability solutions, but the combination of mechanical damage with radiation and vacuum could extend damage and increase the rate of damage so these materials must be tested in these conditions to ensure reliability. These combined stressors are the foundation in which the two main self-healing approaches – extrinsic and intrinsic – must be evaluated.

5.2 Extrinsic vs. Intrinsic Trade-Offs

Due to their relatively simple implementation and autonomous activation, researchers have preferred to use extrinsic self-healing systems. Examples include microcapsule-based self-healing systems and vascular network-based self-healing systems. The primary benefit of extrinsic self-healing systems is their ability to activate autonomously based upon the stress experienced by the material when cracking occurs (Paolillo et al., 2021; Ahmed et al., 2024). As such, extrinsic self-healing systems are well-suited for satellite applications as no human intervention is required. Extrinsic methods remain at the lab-testing phase – proving to be promising candidates for current mission implementations. They are particularly well-suited to secondary structures which may be subjected to cyclic loading and have been shown to restore up to 93% of fracture toughness.

Intrinsic self-healing represents theoretically a better approach for long duration missions since it allows for multiple healing cycles from the same damage site (Wang et al., 2023; Turicek et al., 2026). The major "Achilles' Heel" of the intrinsic mechanism is its dependence on the precise balance between the molecular movement of the polymer chains (chain mobility) and structural stiffness. Typically, modifying the polymer chemistries so that they will form these reversible bonds results in lower glass transition temperature (Tg) values and lower elastic modulus compared to the traditionally used satellite-grade materials and for engineering applications, where a higher Tg is desirable, this presents a material that becomes less mechanically reliable as it softens easily under high temperature.

5.3 Performance Trade-Offs & System Integration

5.3.1 Integration Trade-Offs

The underlying challenge in multifunctional self-healing composites is not achieving autonomous repair itself but is in integrating this capability without compromising the performance requirements for load-bearing satellite materials. In comparison to conventional grade composites, self-healing systems require additional components and activation mechanisms which alter the structure of the material. As a result, improvements in healing performance are frequently accompanied by reductions in mechanical performance, environmental compatibility or manufacturing practicality; therefore, a focus on streamlining is preferred over maximisation.

5.3.2 Strength & Reliability Penalties

The most instantaneous consequence of self-healing integrations is a reduction in baseline mechanical performance. Extrinsic systems such as microcapsules and vascular networks introduce disruptions within the matrix, interrupting effective load transfer, creating stress concentrations which eventually results in reduced tensile strength, stiffness and elastic modulus. This compromise is even more prominent when healing reliability is considered. Autonomous repair depends not only on the efficiency but also on the likelihood that the propagating crack encounters the healing agent. To improve this, it generally requires larger capsules and an increased number of capsules integrated – each of one introducing more disruptions into the matrix. As a result, enhancing healing performance inevitably introduces mechanical penalties that are further amplified with the increase of the reliability of embedded healing systems. This presents a significant limitation for lightweight satellite structures where stiffness and reliability are critical design requirements.

5.3.3 Mitigation Attempts & Limitations

Numerous reinforcement strategies have been proposed to mitigate the reduction in mechanical performance. Carbon nanotubes (CNTs), graphene and other nanosized fillers have been incorporated to recover stiffness and strength after embedding and while maintaining healing functionality illustrated by Veeramani et al. (2024). Although these reinforcements can improve mechanical performance, they introduce new challenges including nanoparticle agglomeration, where the particles tend to cluster together, bringing inconsistent dispersion throughout the polymer matrix. Most importantly, these fillers restrict polymer chain mobility (Krishnakumar et al., 2020) – essential for effective crack closure and bond reformation. Consequently, many reinforcement strategies relocate the issue rather than eliminate it, improving one aspect of performance while reducing another.

A greater limitation lies in the nature of damage that currently available self-healing systems are capable of repairing. Damage in these materials is not limited to small cracks in the polymer matrix, but can also involve fibre breakage, where the main load-carrying components of the composite fail. Current polymer-based healing methods are generally effective at repairing matrix-level damage, such as small cracks or delamination (separation between layers), but they are not able to restore broken fibres (Kessler et al., 2003).

For larger broken reinforcement fibres, which carry the majority of structural load with fibre-reinforced composites, most mechanisms remain unable to provide full structural recovery. Therefore, many lab studies that report high healing efficiencies are limited to the recovery of matrix properties alone rather than complete structural restoration (Cano et al., n.d.). For satellite structure, where mechanical performance depends on fibre strength, this represents a clear limitation that cannot be overcome by mitigation or optimisation alone.

These trade-offs aren't just theoretical but also show up in experimental results. Epoxy coatings prepared by Ma et al. (2020) containing polyurea microcapsules encapsulated with ethylene diamine (EDA) repaired cracks by releasing EDA which chemically reacts. It was found that coatings with 5 wt% microcapsules had 93.57% corrosion resistance efficiency (Ma et al., 2020), so the coatings improved reliability within the satellite. This high healing efficiency is both effective and simple, allowing for longer term satellite missions. The encapsulated EDA had a higher heat resistance with the core material decomposing at 302°C compared to the pure EDA completely decomposing at 159°C (Ma et al., 2020), so reliability at higher temperatures is improved. However, long durability is uncertain as the capsule, once ruptured, loses its healing ability so this single use, finite healing capability reduces the materials long term reliability. There was also some structural weakening that occurred, a trade off that needs further testing to manage. Additionally, this testing was done in seawater/labs (Ma et al., 2020) so the effects of MMOD impacts, vacuum, and radiation has not been tested. These microcapsules also eventually run out, so longevity is a key issue to be addressed when using extrinsic mechanisms.

Collectively, these findings demonstrate the pressing challenges of successful integration alongside structural integrity, environmental capability and other design requirements. While these trade-offs constrain single function self-healing systems, current research is increasingly shifting towards embedding healing with broader multifunctional functionalities.

5.4 Multifunctionality As The Emerging Direction

The increasing development of multifunctional composites further complicates material selection. Modern aerospace structures are expected not only to support mechanical loads but also to perform additional functions such as structural health monitoring, electromagnetic shielding and thermal management (Khan et al., 2026). Self-sensing composites incorporating conductive nanomaterials, including carbon nanotubes and graphene, have demonstrated considerable potential by enabling real-time damage detection through changes in electrical resistance (Tao et al., 2025). This capability complements self-healing mechanisms by allowing damage to be identified before significant structural degradation occurs (Veeramani et al., 2024). However, the integration of conductive fillers introduces additional engineering trade-offs, as increased filler content may alter resin viscosity, affect manufacturing quality and influence fracture behaviour (Khan et al., 2026; Veeramani et al., 2024).

These competing requirements highlight a recurring theme throughout the literature: improvements in one material property frequently introduce compromises elsewhere. Microcapsule systems provide relatively simple autonomous healing but remain limited by single-use activation (Ma et al., 2020). Vascular systems offer repeatable healing but increase manufacturing complexity and may reduce structural efficiency through the inclusion of internal channels (Bond et al., 2008). Intrinsic systems eliminate the need for embedded healing agents but often require external activation and currently face challenges regarding environmental stability (Pernigoni et al., 2021). Similarly, while multifunctional enhancements such as self-sensing significantly improve structural intelligence, they also increase design complexity and present additional manufacturing and qualification challenges (Tao et al., 2025).

Overall, current research suggests that no individual self-healing strategy fully satisfies the demanding performance requirements of aerospace structures operating under extreme conditions (Tserpes and Sioutis, 2025; Pernigoni et al., 2023). Instead, the field is increasingly moving towards integrated multifunctional composite systems that combine structural performance, damage detection and self-healing within a single material architecture. Future progress is therefore likely to depend less on maximising healing efficiency alone and more on optimising the balance between durability, manufacturability, environmental resistance and multifunctional performance (Khan et al., 2026).

There is potential in the development of multifunctional self-healing materials as, so far, self-healing capabilities have mainly been studied as an isolated property rather than discussed in other capacities. By investigating multifunctionality, future costs and weight will be minimised on spacecraft and efficiency can be maximised. Incorporating conductive materials into the composites could possibly allow for electrical conductivity and potentially also improve mechanical performance (Veeramani et al., 2024). Structural sensing, thermal management, and protection against radiation could be combined in multifunctional self-healing composites to allow for damage recognition and restoration to improve performance and reliability of the spacecraft (Khan et al., 2026; Tserpes and Sioutis, 2025). These additional features would also enhance the safety of the spacecraft and its longevity in a volatile environment, including reducing maintenance requirements. Managing trade-offs while still maintaining healing capabilities is a further condition to be considered. A greater focus on healing that is also reliable and beneficial at a larger systems level is needed, emphasising mechanical performance and multifunctional integration is needed to move from laboratory testing to practical implementation (Pernigoni et al., 2021).

5.5 Gaps & Future Research

Within the study of composites, there is a lack of testing in operational space systems and current research has focused on the development of a mix of composites and healing mechanisms, while comparatively structural performance, realistic environmental testing, and multifunctionality is less of a priority.

A current gap is the emphasis on healing efficiency and not structural performance, focusing on bonding mechanisms, catalyst activity, and healing percentages through small-scale testing. Loading conditions like tensile and fatigue stresses that larger aerospace structures operate under are still yet to be widely considered and researched. Veeramani et al. (2024) found that the carbon nanotubes containing composites recovered 90% of their original tensile performance, but they did not evaluate long-term resistance or realistic loading in space. Intrinsic mechanisms such as polyurea-urethane (PUU) with different crosslink densities were studied by Pernigoni et al. (2023) and demonstrated puncture sealing capabilities in spacesuits. However, a lack of further investigation in full-scale structural components and mechanical performance other than scratch, puncture, and impact tests suggests a requirement for further research before being applied in satellites. Research should shift towards understanding how self-healing materials work as engineering structures rather than just chemical systems. Necessary to test fatigue conditions, loading scenarios, structural testing, and healing in impact situations to understand whether these composites can be reliably used in space environments.

6 Conclusion

This paper looked at how far multifunctional self-healing composite materials have come in terms of being able to meet the demands of the space environment as part of satellites orbiting Earth. A major theme of interest was the distinction between two types of self-healing material: extrinsic systems (that use an encapsulated agent to provide passive repair) and intrinsic systems (that use reversible chemical bonds to allow for repeated restoration) (Wang et al., 2023; Kontiza and Kartsonakis, 2024). The findings suggest that extrinsic mechanisms are better suited to initial launch into space since their self-contained activation fits within the limitations of remote-control platforms that cannot be repaired manually. Systems utilising microcapsules based on DCPD were found to achieve 93% efficiency, allowing them to be easily integrated with current manufacturing processes for aerospace grade CFRP (Vintila et al., 2020). However, the primary limitation of extrinsic systems for long term missions is their limited agent supply. While intrinsic systems offer the theoretical ability to last for extended periods of time as needed for deep space exploration, the issue remains that they rely upon externally generated heat or special chemicals that may also limit the mechanical strength of the system (Paolillo et al., 2021).

An important result of this review is that although laboratory studies show high efficiencies in many cases approaching 100%, there has been no study accounting for the additive effects of synergistic environmental degradation. There is a trend towards creating ‘smart’ satellite skin technology by incorporating self-healing properties along with damage sensing and radiation protection into single layers (Khan et al., 2026; Tao et al., 2025). As such, there is still a large gap between the laboratory results and actual operational performance. Results from experimental testing conducted outside of the ISS demonstrate that the combined effects of vacuum degassing, ionising radiation, and thermal cycling can cause polymers to degrade up to 10 times faster than would be expected through independent testing under individual conditions (Suliga et al., 2026). Therefore, while extrinsic mechanisms are considered the industry standard for secondary structures, transitioning to space qualified hardware remains stagnant at TRL 3–4 (Ullah Khan and Jamshed, 2025).

Future development work must emphasise validating the effectiveness of satellite repair systems within a variety of stresses (i.e. thermal, radiation) simultaneously occurring as they would in orbit (Pernigoni et al., 2023). To achieve practical satellite use, researchers need to find an optimal balance between repairing polymer-based structures efficiently and maintaining structural integrity while developing agents capable of withstanding high pressure autoclaving. The direction of future satellite research needs to move away from adapting earth based polymers to develop space qualified materials which combine self-repair properties with real time monitoring capabilities (Tao et al., 2025). It is critical to adopt standardised characterisation methods so that meaningful comparisons can be made on performance characteristics of different material types. The success of future satellites in achieving long-term (>100 years) reliability will depend heavily on the transition of inherent chemistry developed in laboratories into matrix forms for satellite structures (Turicek et al., 2026).

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